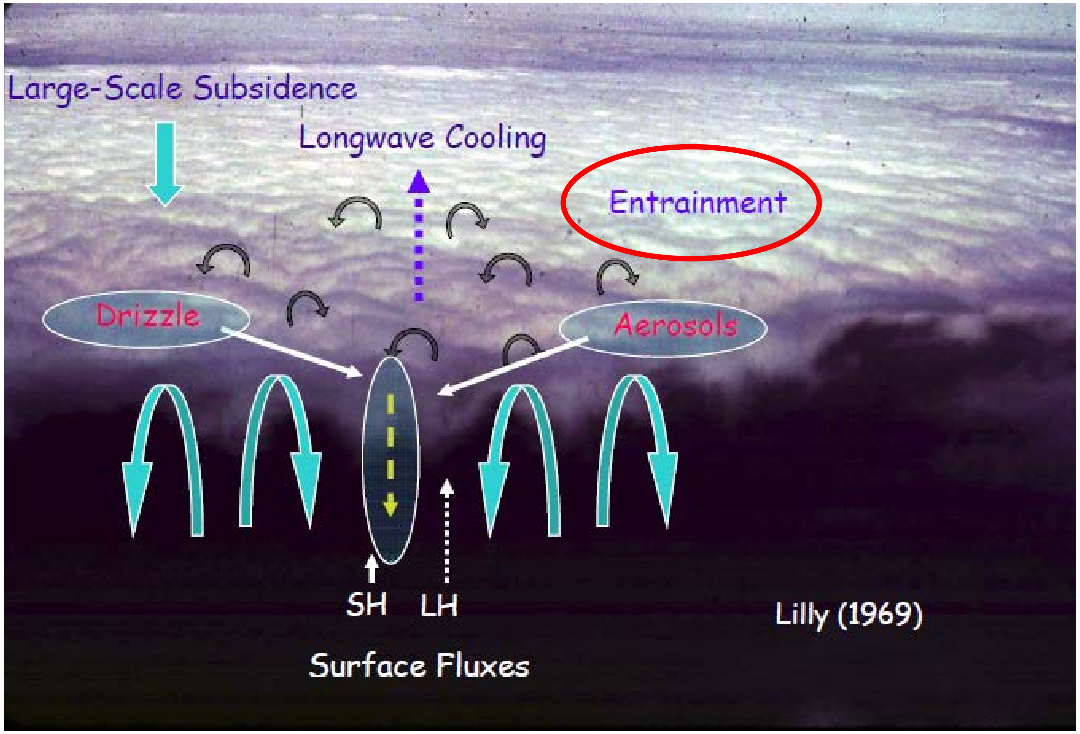
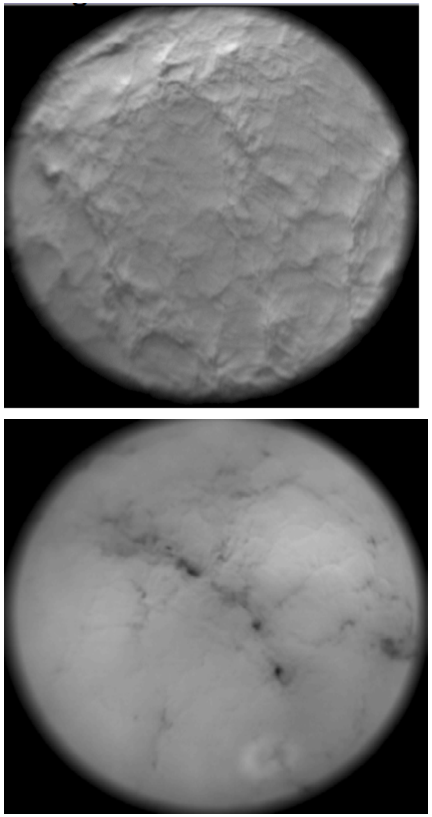
Exploring Stratocumulus Cloud-Top Entrainment Processes and Parameterizations Using Doppler Cloud Radar Observations

Bruce Albrecht and Ming Fang
RSMAS University of Miami





Courtesy: Eric Wilcox

Entrainment Rate Parameterizations—Some History

Turbulence Kinetic Energy (TKE) Constraints

- Kraus and Turner (1967;Tellus)
  - Application: Ocean mixed layer
  - Forcing: Wind
- Lilly (1969;QJRMS)
  - Application: Cloud-topped mixed Layer (stratocumulus)
  - Forcing: Radiative Cloud-Top Cooling
- Tennekes (1973; JAS)
  - Application: Dry Mixed Layer
  - Forcing: Surface Heating

Entrainment Zone TKE Budget and Parameterizations

Zeman and Tennekes (1977)

$$0 = \frac{g}{\theta_o}\left(\overline{\theta_v' w'}\right)_i - \frac{\partial}{\partial z}\left(\overrightarrow{ew'} + \overline{p'w'}/\rho\right) - \varepsilon_i + \text{Shear}$$

Buoyancy | Transport +Pressure | Dissipation

$$\frac{g}{\theta_0} w_e \Delta\theta_v = -\frac{\partial}{\partial z}\left(\overrightarrow{ew'} + \overline{p'w'}/\rho\right) - \varepsilon_i$$

$$C_F \sigma_w^3 / h$$

$$C_D \sigma_w^3 / \ell_i$$

$$w_e = w_{ee} - w_{ed}$$

$$w_e = \frac{C_F \sigma_w^3 / h - \varepsilon_i}{\frac{g}{\theta_0}\Delta\theta_v}$$

$$w_{ee} / w_{ed} = \frac{C_F \ell_i}{C_D h}$$

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Buoyancy

Transport +Pressure

Dissipation

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(A Simple) Entrainment Parameterization

Buoyancy	Transport +Pressure	Dissipation

$$\frac{g}{\theta_0} w_e \Delta\theta_v = -\frac{\partial}{\partial z}\left(\overline{ew'} + \overline{p'w'}/\rho\right) - \varepsilon_i$$

$$C_F \, \sigma_w^3 / h \qquad C_D \sigma_w^3 / \ell_i$$

$$w_e = \frac{C_F \, \sigma_w^3 / h - \varepsilon_i}{\frac{g}{\theta_0}\Delta\theta_v} = w_{ee} - w_{ed}$$

$$w_{ee} / w_{ed} = \frac{C_F \ell_i}{C_D h}$$

If $\ell_i = a\,h$ *,then*

$$w_e = \frac{C_F' \, \sigma_w^3 / h}{\frac{g}{\theta_0}\Delta\theta_v}$$

Observations from aircraft and output from LES have been used to obtain estimates of

Technique	C'_F	Reference
Aircraft	9	Nicholls (1980)
High Res LES (5)	5-8	Bretherton et al (1999)
Low Res LES (9)	6-23	Bretherton et al (1999)

Cloud Radar Observations of SGP Continental Stratocumulus
(no drizzle no bugs)

Approach:

Estimate vertical velocity variance and TKE dissipation rates at cloud top

$$w_e = \frac{C_F \, \sigma_w^3 / h - \varepsilon_i}{\frac{g}{\theta_0} \Delta\theta_v}$$

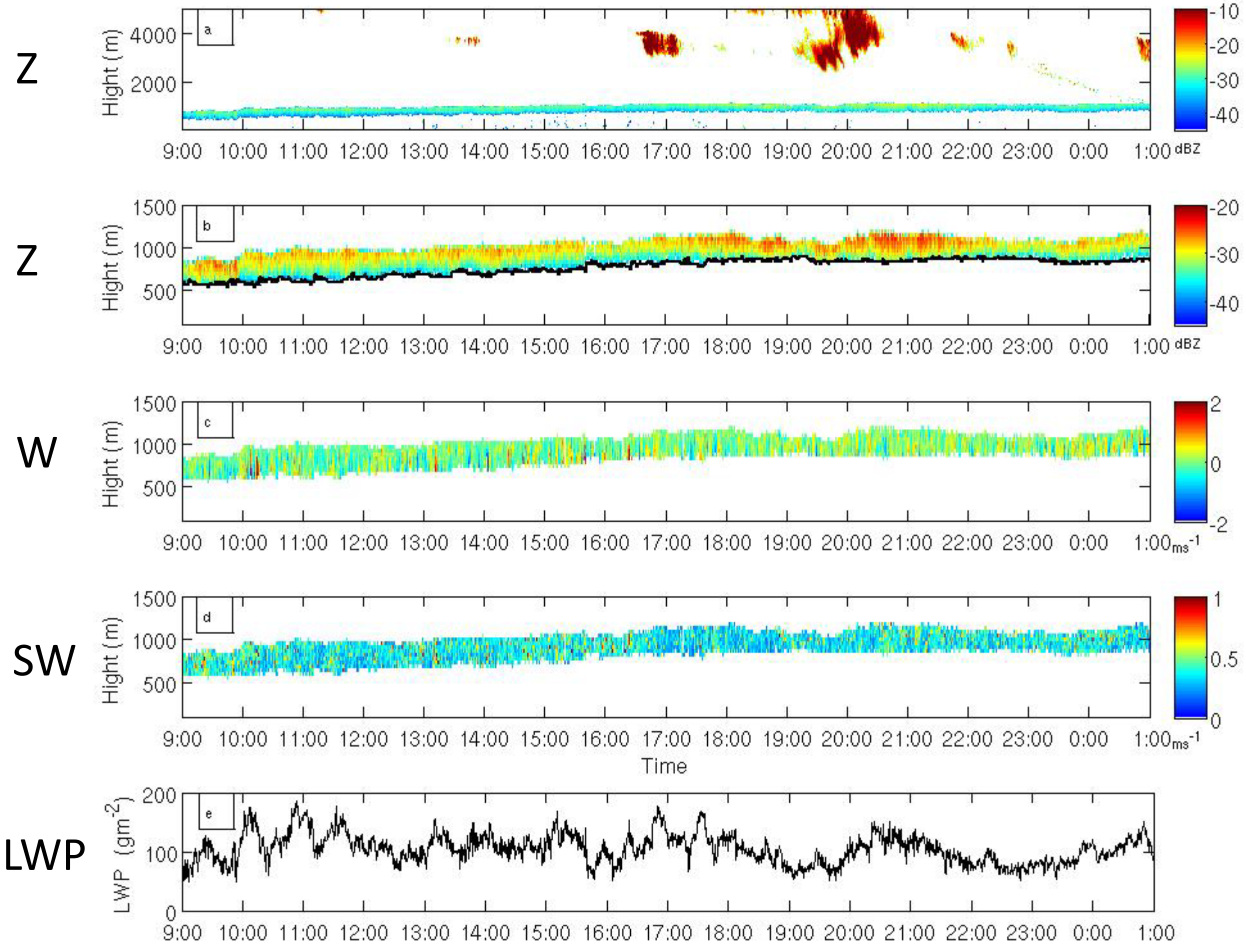
$$C_F \, \sigma_w^3 / h$$

$$C_D \sigma_w^3 / \ell_i$$

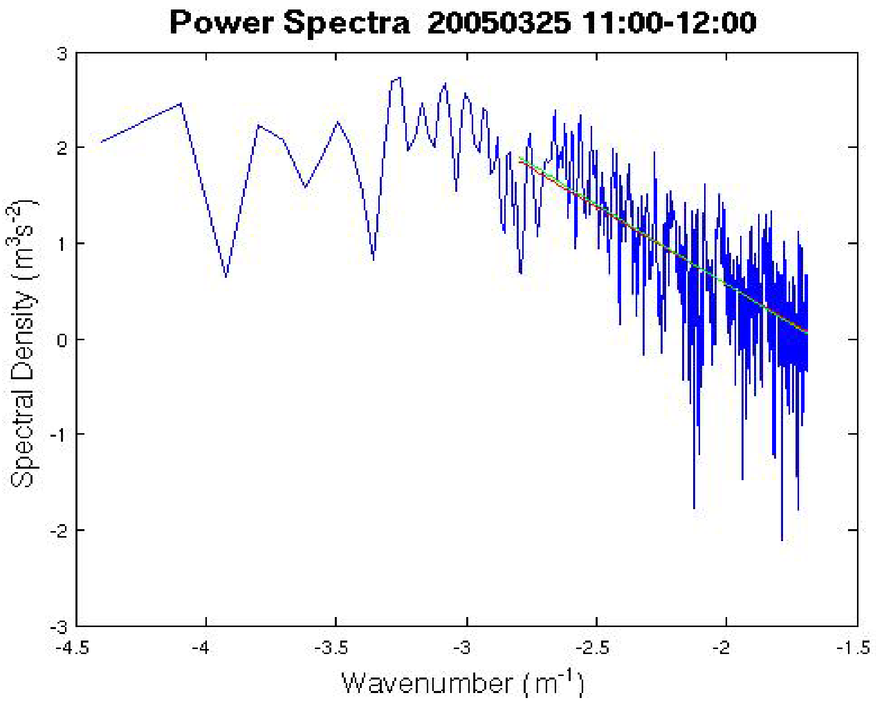
$$w_{ee} / w_{ed} = \frac{C_F \ell_i}{C_D h}$$

MMCR (17H, Lamont, OK)

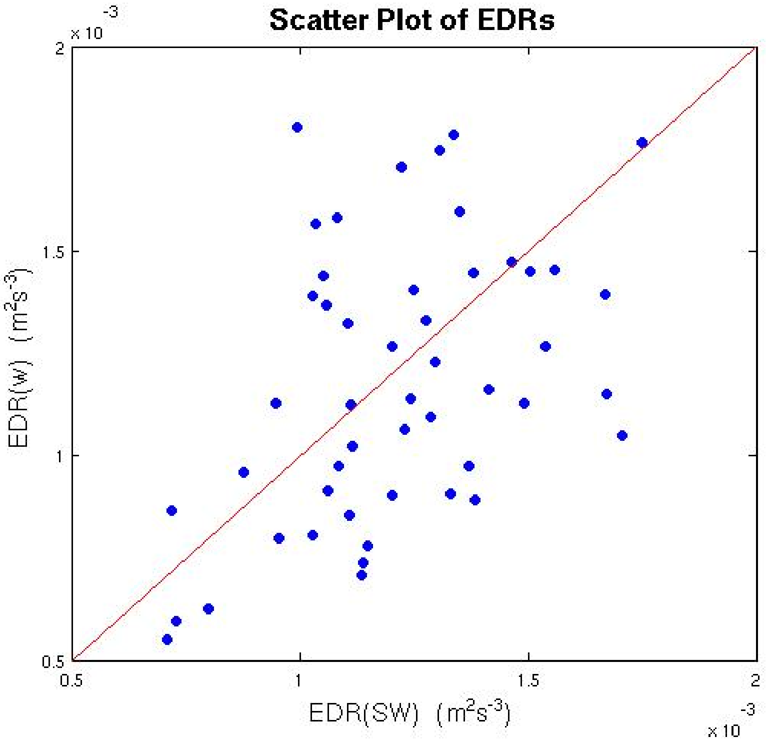
08:00 03/25/2005 – 01:00 03/26/2005



EDR(w) and EDR(SW)



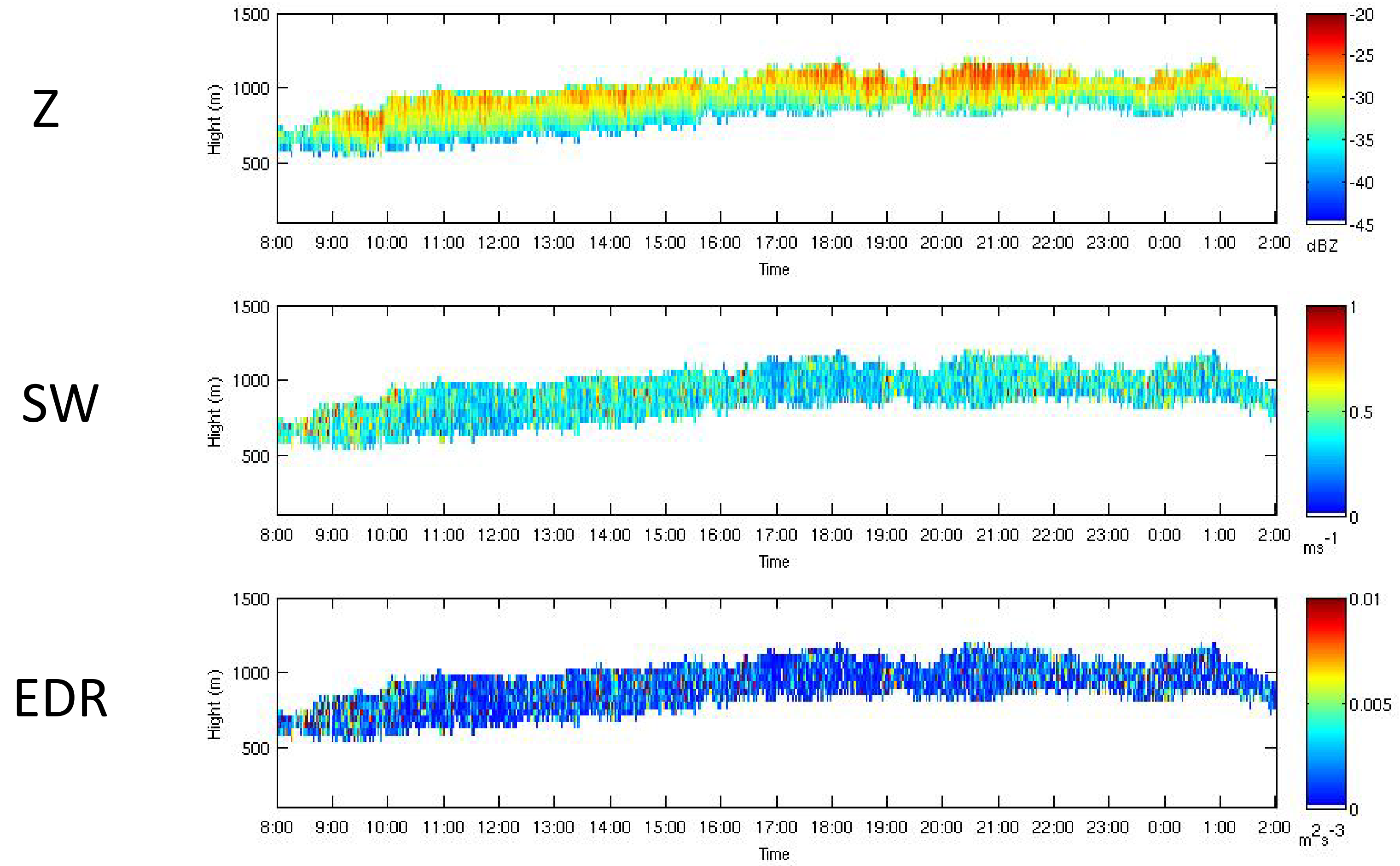
$$\varepsilon = \frac{1}{\delta}\left[\frac{\hat{\sigma}_t^2}{1.35\alpha\left(1-\gamma^2/15\right)}\right]^{3/2}$$



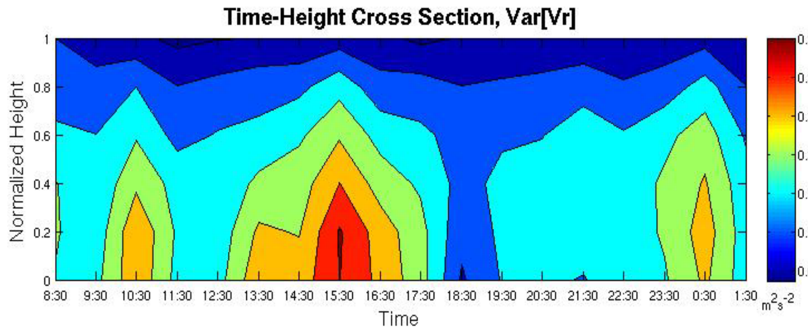
$$S(k) = a\varepsilon^{\frac{2}{3}}k^{-\frac{5}{3}}$$

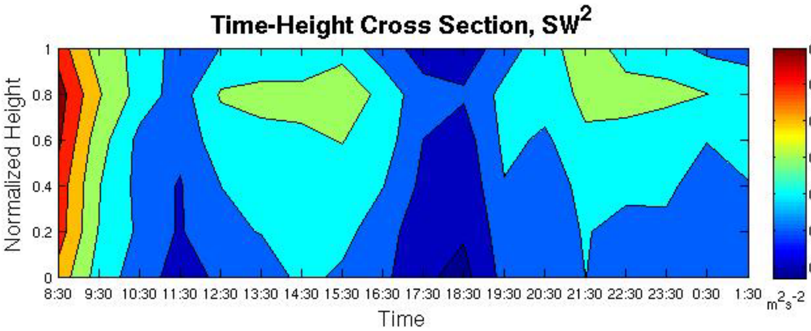
Fang (2013a,b;Bound.Lay. Meteo.
–under review)

18H, Lamont, OK,
08:00 03/25/2005 – 02:00 03/26/2005

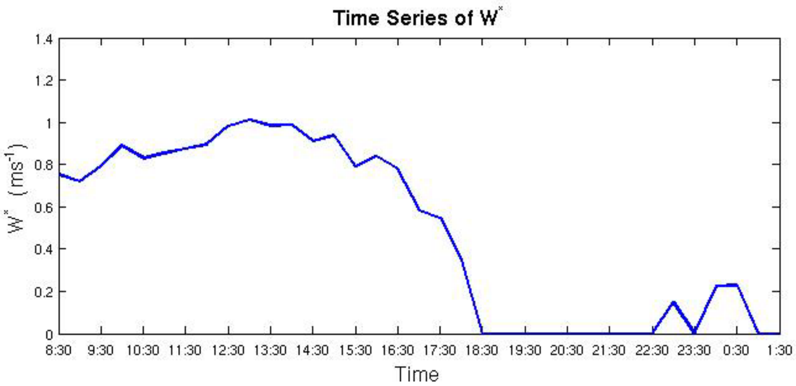


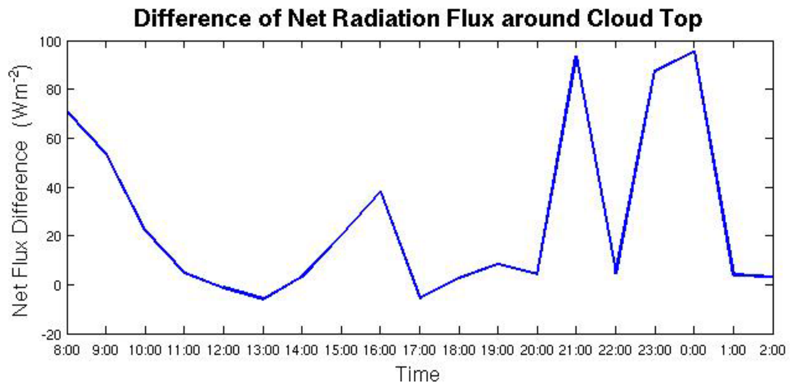
Resolved (Var) and Unresolved Turbulence (SW^2;similar scale to LES subgrid TKE)





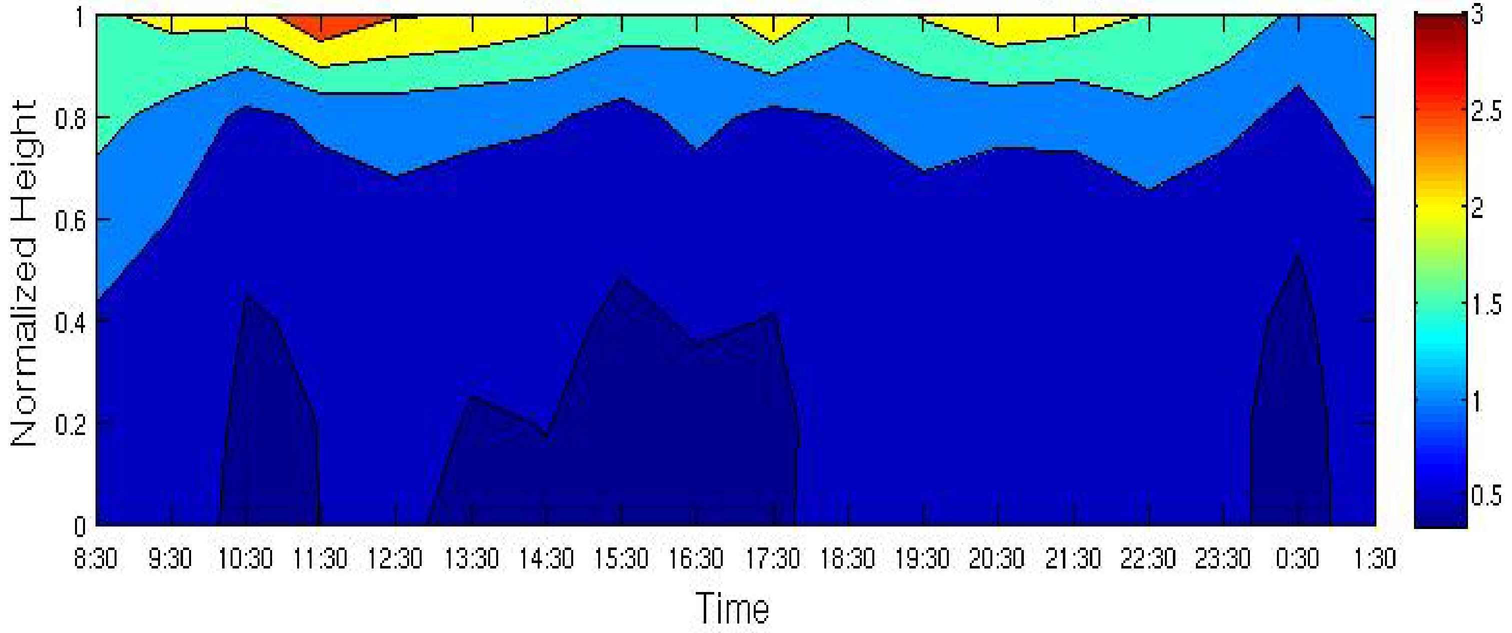
Turbulence Generation--Surface and Cloud Top Forcing



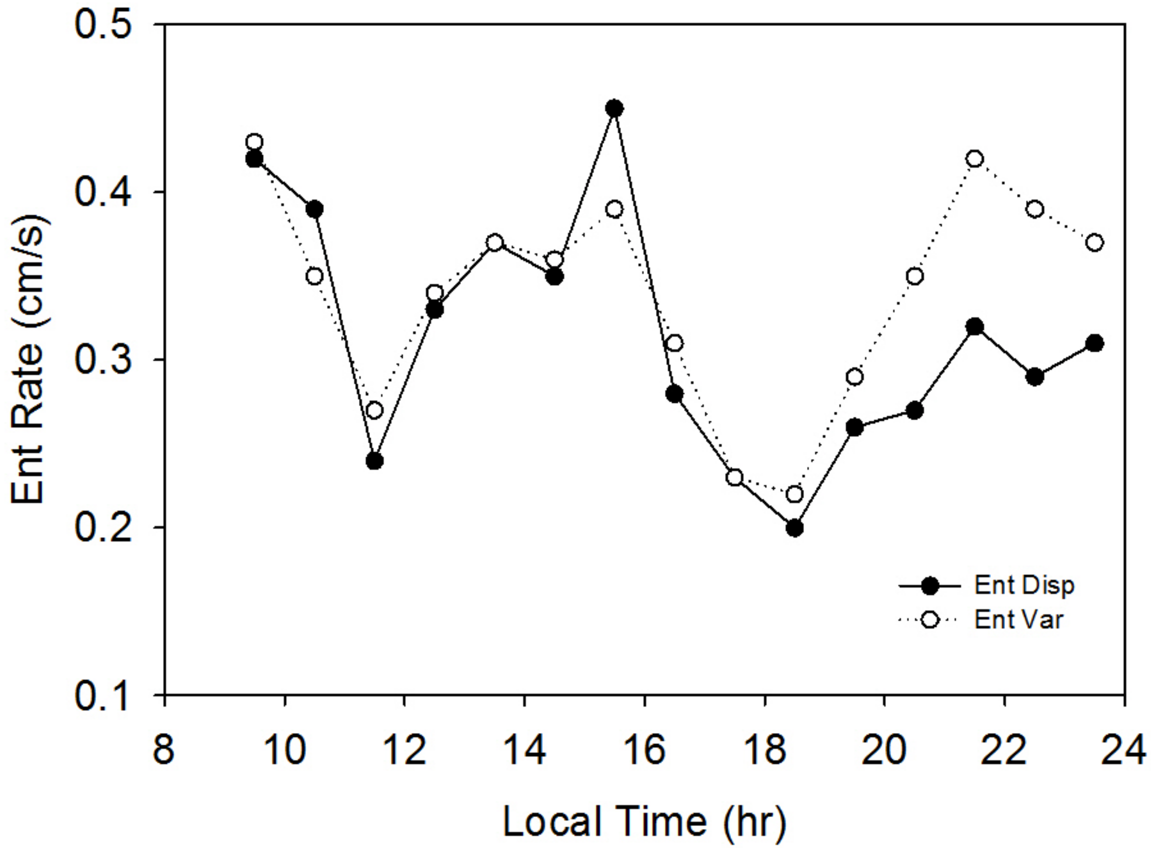


Resolved and Unresolved Turbulence

$SW^2/Var[Vr]$

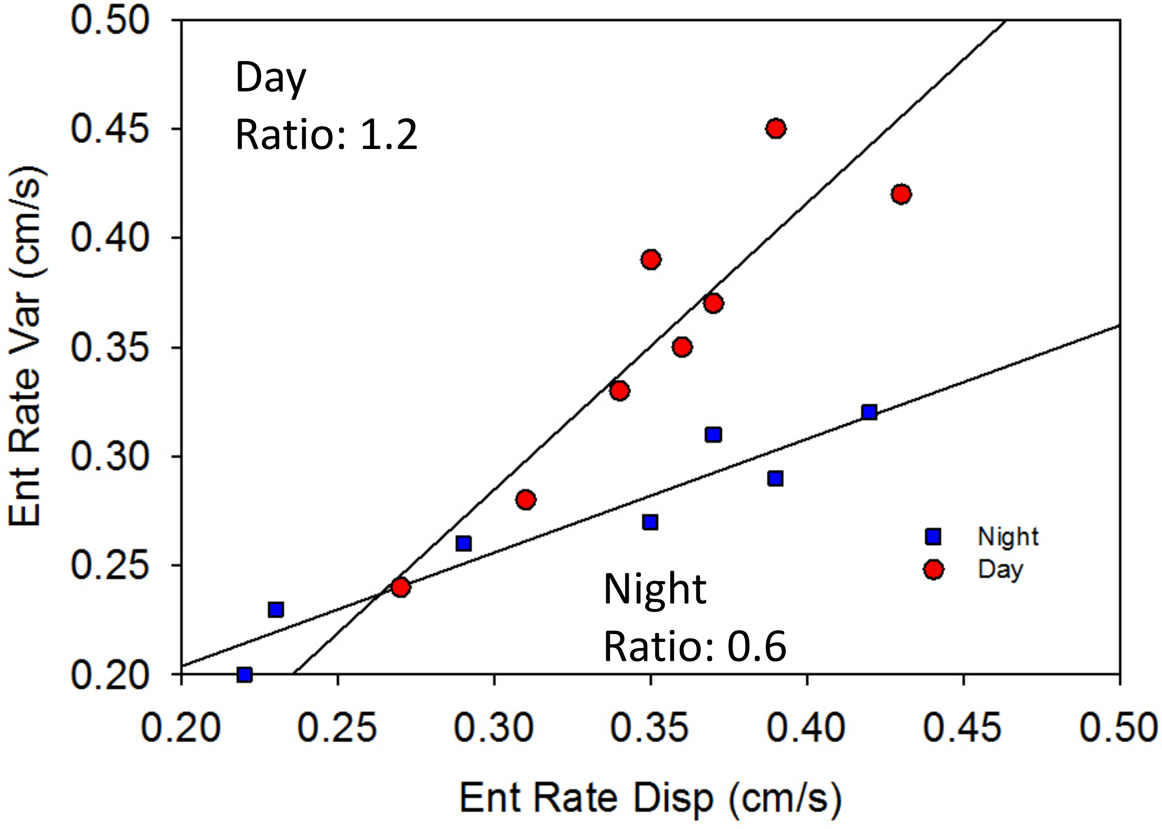


Terms in TKE Entrainment Formulation from MMCR Observations



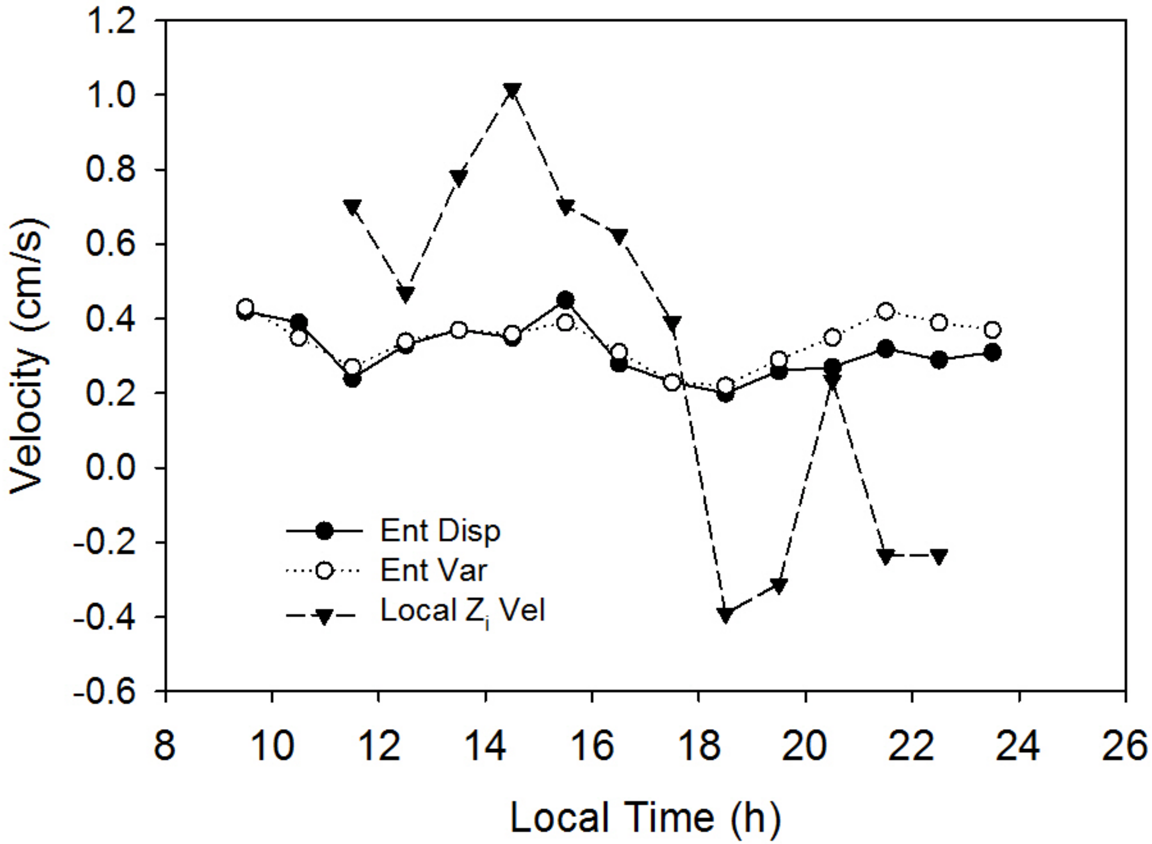
Ratio of entrainment terms

$$w_{ee} / w_{ed} = \frac{C_F \ell_i}{C_D h}$$



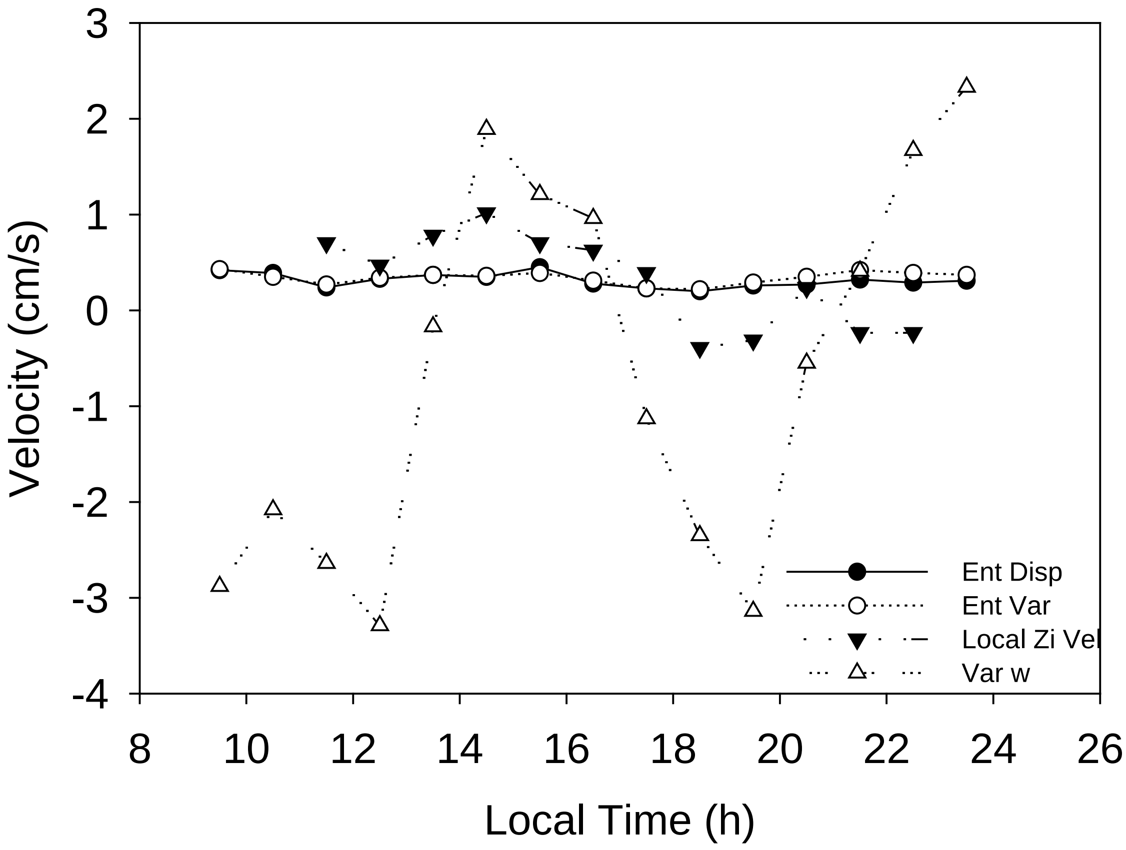
Inversion Budget to Estimate w_e

$$\frac{\partial z_i}{\partial t} = -\vec{V}_H \cdot \nabla z_i + w + w_e$$



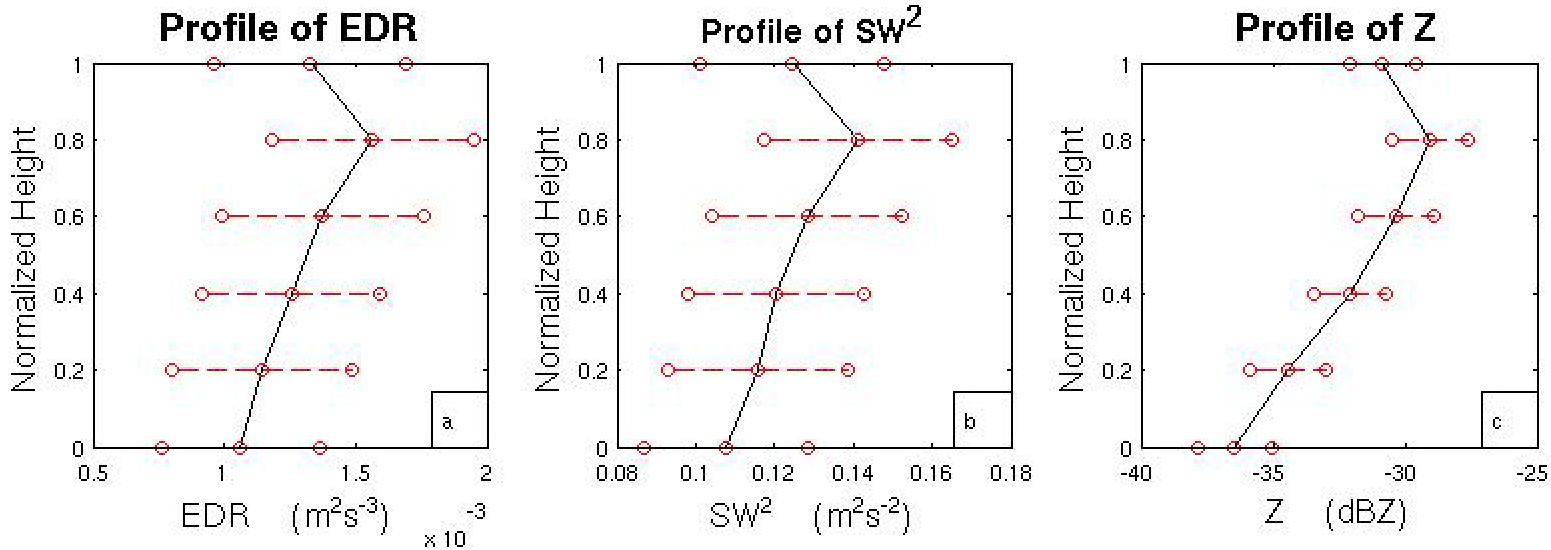
Summary

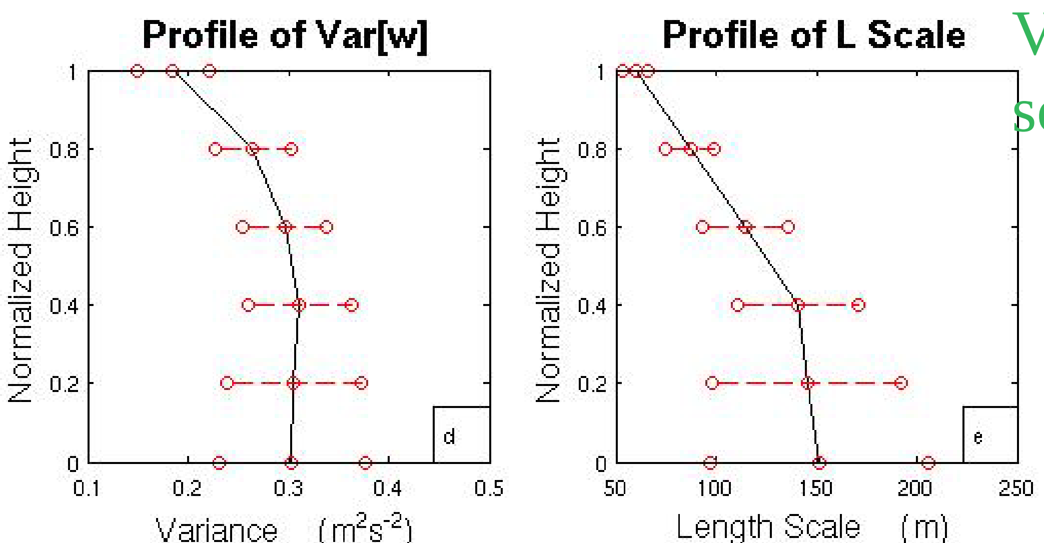
- Entrainment rates are proportional to quantities that can be derived from Doppler radar observations
- Independent estimates of entrainment rates still needed
- Dissipation term is substantial in the TKE budget in the entrainment zone and may depend on scales that vary with turbulence structure.
- Implications for observations
  - TKD dissipation rates may be a direct measure of the entrainment rates
  - ARM observing strategy provide unique cases for process studies
- Implications for models
  - Parameterization evaluation
  - LES evaluation (TKE budgets)



Velocity (cm/s)
3
2
1
0
-1
-2
-3
-4
8
10
12
14
16
18
20
22
24
26
Local Time (h)
Ent Disp
Ent Var
Local Zi Vel
Var w

18H Profiles, EDR, SW^2, Z, Var[w], l_w





Vertical integral length scale

$$l_w = \frac{\sigma_w^{3/2}}{\overline{\varepsilon}}$$